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FLIGHT SIMULATION MOTION-BASE DRIVE ALGORITHMS

Prepared for
Transportation
Development Centre
Transport Canada

by
L. D. Reid and M. A. Nahon
University of Toronto
Institute for Aerospace Studies

December 1986

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The contents of this report reflect the views of the authors and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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17. Abstract This report describes a research program aimed at developing and testing flight simulator motion-base drive algorithms suited to commercial jet transports. Full six degrees-of-freedom motion of a synergistic motion-base was studied. Three forms for these algorithms were considered: classical linear washout, optimal control, and coordinated adaptive washout. Research tasks included developing the necessary equations, implementing the necessary real-time software, and evaluating the performance of the software with the help of airline pilots in a complete flight simulation. The report describes the simulated aircraft and the flight scenarios employed during the evaluation process. The experimental plan and data gathering process are outlined fully. Both subjective pilot ratings and objective performance measures were obtained from seven pilots who evaluated ten different motion-base drive algorithm cases. About half of the experimental trials were used to obtain paired comparison results for four of the ten algorithm cases. The pilot ratings, pilot comments, and objective measures were analyzed. The results highlight both pilot preferences in motion-base drive algorithms and the nature of pilot variability in assessing simulator motion quality.			
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17. Résumé La recherche dont il est rendu compte ici concerne l'élaboration et la mise à l'essai des algorithmes commandant les simulateurs de pilotage dans le domaine de l'aviation commerciale à réaction. Elle a porté sur des plates-formes à effet de synergie et à six degrés de liberté. Trois algorithmes de commande ont été pris en compte: à filtre d'affaiblissement classique à phase linéaire, à filtre à commande optimale et à filtre à commande adaptée. Les chercheurs ont élaboré les équations du mouvement nécessaires, produit les logiciels fonctionnant en temps réel et procédé à l'évaluation des performances, faisant appel à des pilotes de ligne dans un contexte de vol complet simulé. Ce rapport décrit l'avion simulé ainsi que les divers programmes de vol. Il explique le plan d'expérimentation retenu ainsi que la méthode de mesurage. Sept pilotes ont été mis à contribution, évaluant successivement dix gabarits d'affaiblissement. Des cotations subjectives ont été obtenues, complétées d'un mesurage objectif des performances correspondantes de chaque pilote. Enfin, une analyse comparative de tests jumelés a été faite à l'égard de quatre de ces dix gabarits. Les cotations et les commentaires des pilotes ainsi que leurs performances réelles ont été analysées, débouchant sur des constatations relatives aux choix opérés par les pilotes et la nature des traits caractéristiques expliquant la diversité des appréciations concernant la qualité de la simulation du mouvement.			
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SUMMARY

Flight simulators are now an integral part of the airlines' infrastructure and they impact significantly on both the economics and the safety record of the industry. As a result, there is a strong incentive to improve the training effectiveness of these devices in the hopes of achieving even greater benefits. This study was directed towards one aspect of this process, namely the enhancement of the motion cues presented to pilots in flight simulators. At present, most flight simulators employed by the airline industry use motion-drive software based on classical washout algorithms dating back almost 20 years. In the intervening years, several alternative algorithms have been proposed based on modern control theory. Two of these, optimal control and adaptive washout, are the focus of this project.

The first phase of the work involved the implementation of the various motion-base drive algorithms on the Flight Research Simulator at the University of Toronto's Institute for Aerospace Studies (UTIAS). A number of computer-based tests were then carried out on the software in order to tune it to the present application.

The second phase consisted of developing the UTIAS simulator to a level where it could represent a heavy jet transport. A number of flying tasks were then generated that would fully exercise the motion-base drive algorithms under realistic conditions. This involved flight through turbulence, a landing, a take-off, and recovery from an engine failure.

The third and final phase of the study employed seven airline pilots to evaluate the realism of the motion cues generated by the various motion-base drive algorithms. The pilots carried out the same flight sequence for each of 10 different algorithm formats and rated their properties using subjective rating scales. In addition, objective measurements were taken of their flying performance on each trial.

The following results and conclusions were found for this study.

- (1) The pilots preferred physical motion to be present in the simulator. They felt that it added to the realism of the simulation and was helpful in the piloting task.
- (2) In general, each pilot was fairly consistent in the ratings of the various motion-base drive algorithms. That they were not perfectly consistent can be seen by reading the pilot comments.
- (3) There was considerable variability among pilots in the rating process. This is demonstrated by the pilot comments and the paired comparison test analysis.
- (4) In spite of the variability reported in (3) above, trends in pilot ratings caused by the different motion-base drive algorithms were significant.
- (5) Under the attribute "overall assessment", the pilots ranked the motion-base drive algorithms as follows (from best to worst): AW2, CW2, CW3, AW1, CW1, AW3, OC2, OC1, OC3, NM.
- (6) As indicated by the pilot comments and the pilot ratings, it is possible for the simulator motion amplitude to be judged too great even though it is well below that expected in an actual aircraft.

Based on the experience gained in carrying out this project, a number of recommendations have been formulated:

- (1) From the good performance of the coordinated adaptive washout algorithm, it appears worthwhile to investigate its further improvement through a systematic study of alternative forms for its cost function. In particular, forms which remain flatter away from the motion limits then rise more steeply than the present quadratic form should be sought. As well, more sophisticated cost functions should be used to give the algorithm more 'intelligence' to handle specific situations.
- (2) Further tuning of all the present motion-base drive algorithms should be directed towards areas giving rise to pilot complaints.
- (3) Motion-base drive algorithms should be selected to suit:
 - (i) the individual pilot,
 - (ii) the individual degree-of-freedom,
 - (iii) the individual maneuver,
 - (iv) the particular simulator.

A means of dynamically achieving this goal should be developed and tested.

- (4) A computer-based "expert system" should be developed to replace the designer in the tedious and demanding motion-base algorithm tuning process.

SOMMAIRE

Les simulateurs de vol font maintenant partie intégrante de l'infrastructure des sociétés de transport aérien, et leur impact sur l'économie et la sécurité de l'exploitation se fait de plus en plus marqué; où l'intérêt manifeste d'en améliorer les performances dans l'espoir d'en tirer le plus grand parti possible. La présente recherche a été axée sur l'un des aspects de la simulation, à savoir le rehaussement des impressions de mouvement communiquées aux pilotes. Jusqu'ici, la plupart des modèles mathématiques décrivant les mouvements imprimés à un simulateur de vol intégraient des algorithmes de filtrage à affaiblissement classiques, datant de quelque 20 ans. Or, entre-temps, un grand nombre de nouveaux algorithmes ont été proposés, fondés sur les avancées dans le domaine des asservissements. Les algorithmes explicités dans le présent rapport appartiennent à deux systèmes différents, le premier à commande optimale et le second à commande adaptative.

La première phase de la recherche a concerné l'intégration des divers algorithmes envisagés dans le simulateur de vol appartenant à l'Institute for Aerospace Studies (UTIAS) de l'université de Toronto, suivie de contrôles assistés par ordinateur cherchant à régler le logiciel en fonction de l'application visée.

L'objectif de la deuxième phase a été de rendre le simulateur apte à simuler le vol des gros porteurs. Pour cela, il a fallu décrire un certain nombre de tâches de pilotage formant un programme de vol précis et mettant les algorithmes à pleine contribution, dans des circonstances aussi réalistes que possible: décollage, atterrissage, turbulences et même panne de moteur.

Pour la troisième phase, il a été fait appel à sept pilotes chargés d'évaluer le réalisme des impressions de mouvement simulées par les différents algorithmes. Chaque pilote a exécuté le même programme de vol pour chacun des dix gabarits d'affaiblissement étudiés, attribuant à chacun d'eux une cotation purement subjective. Cette appréciation personnelle a été complétée de mesurages objectifs des performances correspondantes du pilote.

Cette méthode de recherche a donné les résultats suivants:

- 1) Les pilotes souhaitent que le simulateur imprime des sensations physiques de mouvement qui, à leur avis, ajoutent au réalisme et les aident dans la tâche de piloter.
- 2) Les cotations attribuées par un même pilote aux divers algorithmes étaient grosso modo cohérentes. Les commentaires éclairent les variations constatées dans les appréciations.
- 3) Par contre, les cotations ont fortement varié d'un pilote à l'autre, comme le montrent leurs commentaires et l'analyse comparative des tests jumelés.

- 4) Malgré la diversité des cotations soulignée à l'alinéa 3, l'évolution des cotations d'un même pilote demeure significative.
- 5) Sous la rubrique "Évaluation globale", les cotations attribuées par les pilotes ont été les suivantes (par ordre décroissant): AW2, CW2, CW3, AW1, CW1, AW3, OC2, OC1, OC3 et NM.
- 6) Les commentaires et les cotations des pilotes font ressortir que l'amplitude de mouvement imprimée par le simulateur peut être ressentie comme trop forte même si elle est bien inférieure à l'amplitude anticipée dans un vrai aéronef.

La recherche a permis de formuler les recommandations suivantes:

- 1) Les bonnes performances de l'algorithme à commande adaptative justifient son perfectionnement par la recherche systématique de différentes formes de fonction de coût. Ce qu'il faut surtout rechercher ce sont des courbes d'affaiblissement plus plates loin des limites du mouvement, mais qui se redressent ensuite à un angle plus aigu que dans le cas des fonctions de coût quadratiques actuelles. En outre, il faudra rechercher des fonctions de coût plus fines, rendant l'algorithme plus "intelligent" et mieux en mesure de satisfaire à une situation donnée.
- 2) Le réglage plus fin de tous les algorithmes actuels devrait être infléchi dans le sens d'une élimination progressive des causes d'insatisfaction de la part des pilotes.
- 3) Les algorithmes devraient être spécifiques:
 - i) au pilote
 - ii) au degré de liberté
 - iii) à la manœuvre, et
 - iv) au simulateur

considérés; une méthode dynamique permettant de réaliser cet objectif devrait être étudiée et mise à l'essai.

- 4) Le réglage des algorithmes, processus toujours laborieux et coûteux, devrait être confié à un système expert informatisé et non à un spécialiste.

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1. INTRODUCTION

The research undertaken in this study was aimed at improving the realism of flight simulator motion. A secondary goal was the commissioning of the UTIAS Flight Research Simulator. The first two phases of this project involved a survey of motion generation techniques in the technical literature, the identification of promising ones for further study and the development of the simulator to a state which would allow this study to be carried out. The third and final phase consisted of an evaluation of the selected motion techniques by airline pilots in a realistic flight environment.

Three types of algorithms were tested: the 'classical', the 'optimal' and the 'adaptive' washout. Since each algorithm can be tuned to alter the motion it generates, three tuning levels for each type were investigated. As well, a 'no-motion' case was included for comparison purposes.

A subjective evaluation consisted of having the pilots fill out the rating sheets shown in Figure 1 and respond to six short questions. An objective evaluation consisted of an analysis of the accuracy with which the pilots flew the designated flight path.

Seven pilots participated in the first part of the experiment which consisted of ten long flights (20 minutes) around the airport — one with each of the algorithms. Six of these pilots then went on to fly short (5 minute) paired comparisons of a subset of four of the ten motion algorithms.

2. FLIGHT SIMULATOR

The UTIAS Flight Research Simulator was employed in the present study. The simulator is shown in Figures 2 and 3. The motion-base is a CAE Series 300 six degrees-of-freedom unit incorporating hydrostatic bearings. The complete system is run at a 20 Hz update rate by a Perkin-Elmer 3250 digital computer. The major subsystems are depicted in Figure 4. The pilot flies the simulator just as he would an actual aircraft. He receives the necessary inputs from the forward view display of the outside world, the instruments, the physical motion of the simulator and the sound system, all of which are driven by the digital computer in response to his control inputs. The proper synchronization of these various items is achieved by the flight equations programmed on the computer. The intent of this project was to improve the computer programs (or algorithms) which make up the block labelled 'washout filters'. This block receives the aircraft motion which would have occurred following the pilot's control inputs and calculates how to move the simulator to make him perceive that he is undergoing those same aircraft motions.

It should be noted that since the instruments and visual display are fed from a point upstream of the simulator motion generation, they are completely unaffected by the simulator motion. As well, it should be noted that the motion to which the pilot is subjected is affected not only by the washout filters, but also by the buffet generation and by the accuracy of the flight equations (e.g., turbulence model and yaw damper model). In order to weed out some of these effects from the pilots' responses, we

stressed the need for them to evaluate the motion in comparison to the visual and instrument displays.

3. MOTION-BASE DRIVE ALGORITHMS

The three algorithms tested were the 'classical', the 'optimal' and the 'adaptive'. The 'classical' algorithm of which there are various forms, and which is presently used by most simulator manufacturers is relatively straightforward. As a result, it is easy to adjust for pilot preferences but can be inflexible. Because it is a fixed filter, it must be adjusted for a worst case maneuver to avoid hitting the simulator's motion limits and any less stringent maneuver produces proportionately less motion. Thus these algorithms often generate very little motion and continually underutilize the motion-base's capability. As well the tuning is a trial-and-error process which must be performed by an experienced engineer in conjunction with an experienced pilot. Various papers have appeared in the technical literature claiming that improvements in the motion quality could be obtained by implementing more complex algorithms.

The 'optimal' filters are also fixed filters (developed at MIT), and thus must also be designed for a worst case. However, the design method follows a preset procedure (using optimal control theory). Once all the necessary software is developed, it appeared that an understanding of the filters would not be necessary in order to tune them. However, it has since been found that the tuning process is not as straightforward as it first seemed, and that these filters can often be more difficult to tune than the 'classical' filters. Thus, although the 'optimal' filters can be tuned to yield realistic motion, they do not offer any inherent advantages over the 'classical' filters and will not be pursued further. A joint NASA-MIT comparison of these filters with NASA's 'classical' filters in a two degrees-of-freedom simulation at NASA-Ames recently yielded similar results.

The 'adaptive' filters (developed at NASA-Langley) are variable filters and do not have to be designed for a worst case. They are essentially intelligent enough to know when the simulator gets close to its limits and adjust themselves automatically to avoid hitting the limits. Thus they make more efficient use of the motion-base's capabilities. As well, these filters are formulated in such a way as to adjust themselves to follow the aircraft motion as best as possible within the motion-base's constraints. Their disadvantages are that they are more difficult to tune than the 'classical' filters, and that the motion they produce depends not only on the pilot's control inputs but also on how close the simulator is to its limits. We were interested in seeing whether the pilots would detect the latter feature (they did, but only sporadically).

Three different levels of tuning for each of the three motion-base drive algorithm types described above were employed. This process involved choosing washout filter parameters which would yield a range of simulator motions, from the most active (while still remaining within the limits of the motion-base of the UTIAS Flight Research Simulator) to the least active for a given set of aircraft maneuvers. These cases were assigned the following designations, with the more restrictive algorithms having the larger numerical code:

- (1) classical washout cases - CW1, CW2, CW3,
- (2) optimal control cases - OC1, OC2, OC3,
- (3) adaptive washout cases - AW1, AW2, AW3,
- (4) no-motion case - NM.

4. TEST RESULTS

4.1 Pilot's Control Activity and Performance

In general it was found that there was no influence of motion drive algorithm type on pilot's control activity and performance. The greatest variation in performance was noted for the control of rate of descent (see Figure 5 for example).

4.2 Pilot Ratings

In spite of the lack of influence of the motion-base algorithms on such measures as control activity and task performance, there was a definite strong impact on pilot opinion. This was reflected in pilot comments and pilot ratings. Figure 6 shows the summary of pilot ratings of simulator response to wheel inputs using the UTIAS scale. Figure 7 does the same for the overall rating item included on the MIT scale. It can be seen that the mean values of the ratings (averaged over 7 pilots) are affected by the motion-base drive algorithm form. An analysis of variance was performed on the results from each rating scale. It was found that treatment (algorithm) effects were highly significant. In order to highlight the individual items contained in both rating scales an analysis of variance was performed on subsets of the data corresponding to each item in isolation. In order of decreasing significance it was found for the UTIAS scale that the motion-base drive algorithm type affects pilot ratings of Ground Contact, Turbulence, Column, Wheel, and Throttle with little impact on Pedals. For the MIT scale the corresponding sequence was Smoothness, Amplitude, Sense, Overall, and Phase Lag with little impact on Disorientation and Discomfort.

Table 1 summarizes the rank order of the ratings based on the average results. Cases with identical mean ratings are joined together by underlining them. It can be seen that the sequences are somewhat variable across the rated attributes. Despite this it is possible to see some trends. For example:

- (1) NM appears most often towards the extreme right hand side of the array, indicating that the no-motion algorithm is not very well liked. (The Smoothness case where NM is ranked first is not relevant.)
- (2) AW2 appears most often towards the extreme left hand side of the array, indicating that it produced the best motion quality in most cases. This is borne out by its ranking as number one under the attribute "Overall".
- (3) In the "Overall" attribute rating CW2 is ranked second to AW2. This is consistent with the performance of CW2 in the other categories.
- (4) The best of the optimal controller algorithms is OC2. Its performance is found to be, on average, slightly to the right of centre in Table 1. However OC2 was ranked lower than CW2 and AW2 in almost every category.

- (5) From the "Overall" attribute rating it is seen that all the optimal controller algorithms are ranked below all the classical and adaptive algorithms. The classical and adaptive rankings are intermixed.

5. CONCLUSIONS AND RECOMMENDATIONS

- (1) In the present study the motion-base drive algorithms had almost no impact on flying performance and control activity.
- (2) The pilots preferred physical motion to be present in the simulator. They felt that it added to the realism of the simulation and was helpful in the piloting task.
- (3) In general, each pilot was fairly consistent in his ratings of the various motion-base drive algorithms.
- (4) There was considerable variability among pilots in the rating process. This is demonstrated by the pilot comments and in the paired comparison test analysis.
- (5) In spite of the variability reported in (4) above, the trends in pilot ratings caused by the different motion-base drive algorithms were significant in the cases of the attributes Column, Wheel, Throttle, Turbulence, Ground Contact, Smoothness, Sense, Amplitude, Phase Lag and Overall. There were no significant trends noted for Rudder Pedals, Discomfort and Disorientation.
- (6) Under the attribute Overall, the pilots ranked the motion-base drive algorithms as follows (from best to worst): AW2, CW2, CW3, AW1, CW1, AW3, OC2, OC1, OC3, NM.
- (7) As indicated by the pilot comments and the pilot ratings, it is possible for the simulator motion amplitude to be judged as too great even though it is well below that expected in an actual aircraft.
- (8) Based on the good performance of the coordinated adaptive washout algorithm it appears worthwhile to investigate its further improvement through a systematic study of alternate forms for its cost function. In particular, forms which remain flatter away from the motion limits then rise more steeply than the present quadratic form should be sought. As well, more sophisticated cost functions should be used to give the algorithm more 'intelligence' to handle specific situations.
- (9) Motion-base drive algorithms should be selected to suit
 - (i) the individual pilot,
 - (ii) the individual degree-of-freedom,
 - (iii) the individual maneuver,
 - (iv) the particular simulator.

A means of dynamically achieving this goal should be developed and tested.

Table 1. Summary of Average Pilot Ratings (Best → Worst)

Column	AW2	CW1	CW2	AW1	OC2	CW3	AW3	OC3	OC1	NM
Wheel	AW2	CW2	OC2	AW1	CW3	CW1	AW3	OC3	OC1	NM
Pedals	CW2	AW2	CW1	<u>AW1</u>	<u>CW3^b</u>	OC3	OC2	OC1	AW3	NM
Throttle	AW2	CW1	CW2	<u>AW1</u>	<u>OC2</u>	OC3	OC1	AW3	CW3	NM
Turbulence	AW2	CW2	AW1	CW3	CW1	AW3	OC2	OC1	NM	OC3
Ground Contact	AW1	CW1	AW2	CW3	OC1	CW2	OC3	OC2	AW3	NM
Smoothness	NM	AW3	CW3	AW2	OC2	CW2	AW1	CW1	OC1	OC3
Sense	AW2	CW3	<u>CW2</u>	<u>OC2</u>	<u>AW3</u>	NM	CW1	<u>OC1</u>	<u>OC3</u>	<u>AW1</u>
Amplitude ^a	OC3	AW1	CW1	OC1	CW2	OC2	AW2	CW3	AW3	NM
Phase Lag	AW2	CW3	<u>CW2</u>	<u>OC2</u>	<u>NM</u>	AW3	CW1	OC3	AW1	OC1
Discomfort	<u>AW2</u>	<u>AW3</u>	<u>CW2</u>	<u>CW3</u>	<u>OC2</u>	NM	<u>OC1</u>	<u>AW1</u>	CW1	OC3
Disorientation	<u>CW1</u>	<u>CW2</u>	<u>AW2</u>	<u>AW3</u>	<u>CW3</u>	<u>OC2</u>	<u>OC3</u>	<u>AW1</u>	NM	OC1
Overall	AW2	CW2	CW3	AW1	CW1	<u>AW3</u>	<u>OC2</u>	OC1	OC3	NM

^aMost → Least

^bUnderlining joins identical averages

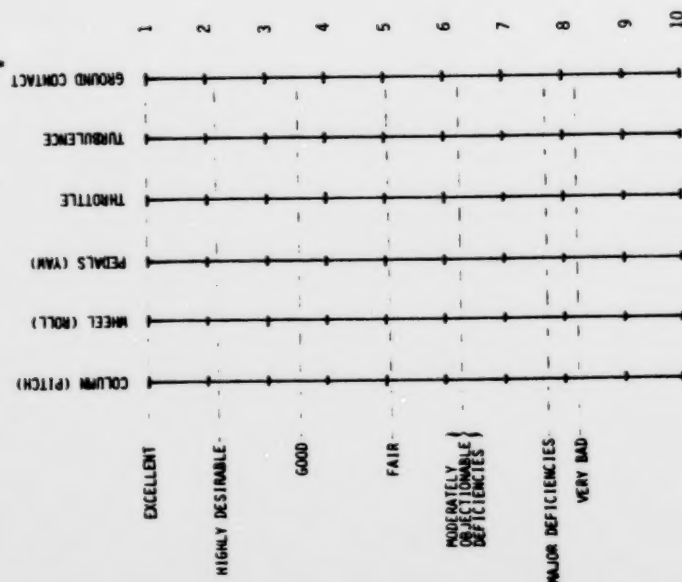
PILOT _____
 RUN NO. _____

PILOT RATING SCALES

The action of the simulator will be rated on the following seven scales:

Attribute	Rating	Response
	1	
	5	
SMOOTHNESS:	extremely smooth-comparable with fixed base	extremely jerky limit of tolerance
SENSE:	definitely correct as in aircraft	totally reversed
AMPLITUDE:	no motion experienced	at least twice that expected
PHASE LAG:	none experienced	at least 180°
DISCOMFORT:	none experienced	cannot continue maneuver
DISORIENTATION:	none experienced	cannot perform maneuver
OVERALL:	excellent	extremely poor

PILOT _____
 RUN NO. _____



* Includes touchdown bump, braking and steering.

UTIAS SCALE

MIT SCALE

FIGURE 1 PILOT RATING SCALES

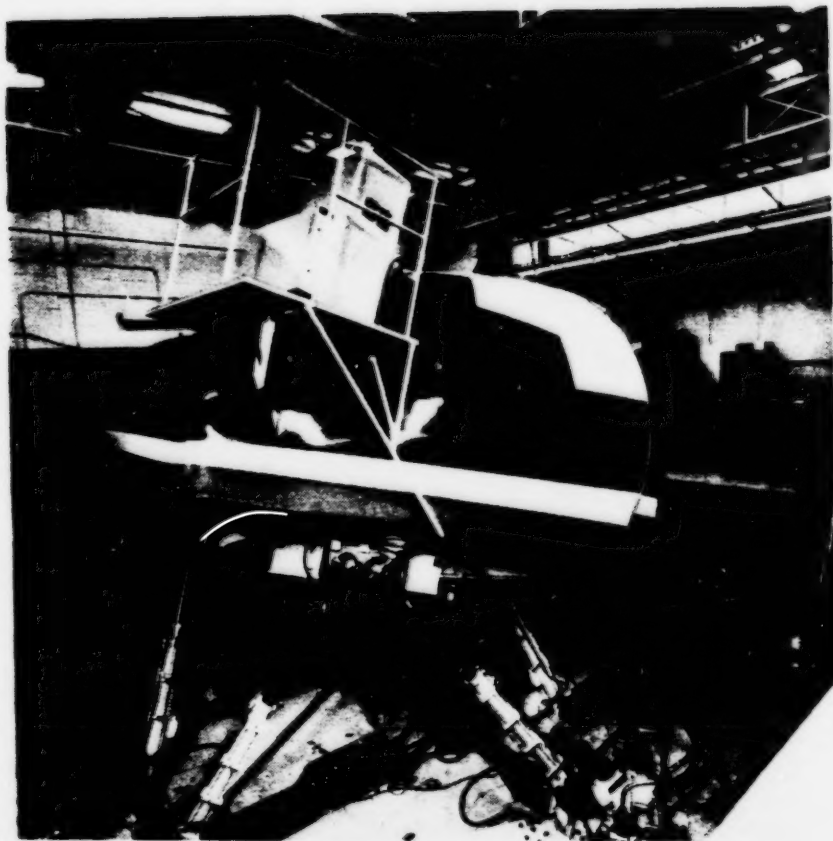


FIGURE 2 UTIAS FLIGHT RESEARCH SIMULATOR - EXTERIOR



FIGURE 3 UTIAS FLIGHT RESEARCH SIMULATOR - INTERIOR

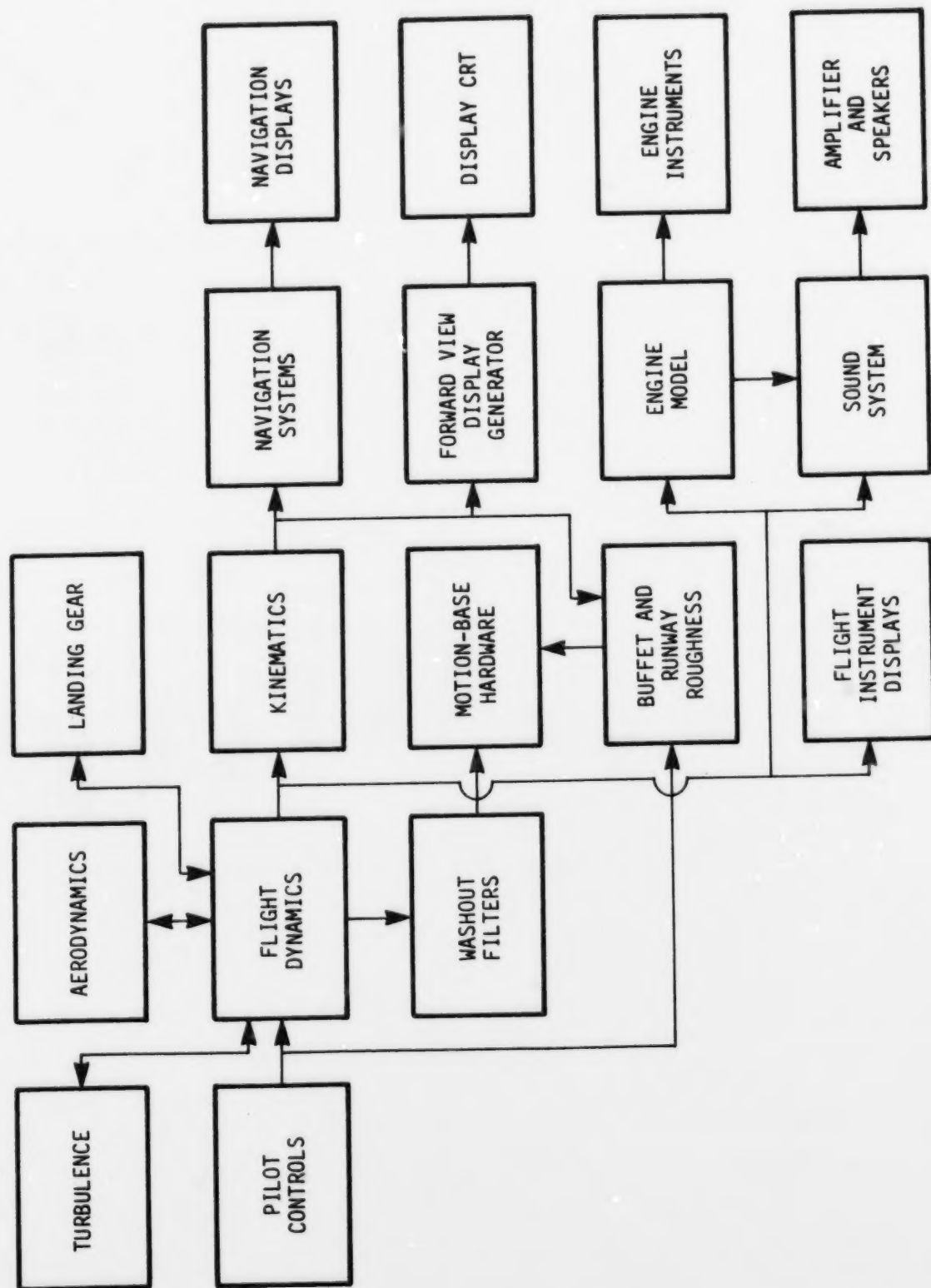


FIGURE 4 SIMULATOR SUBSYSTEMS

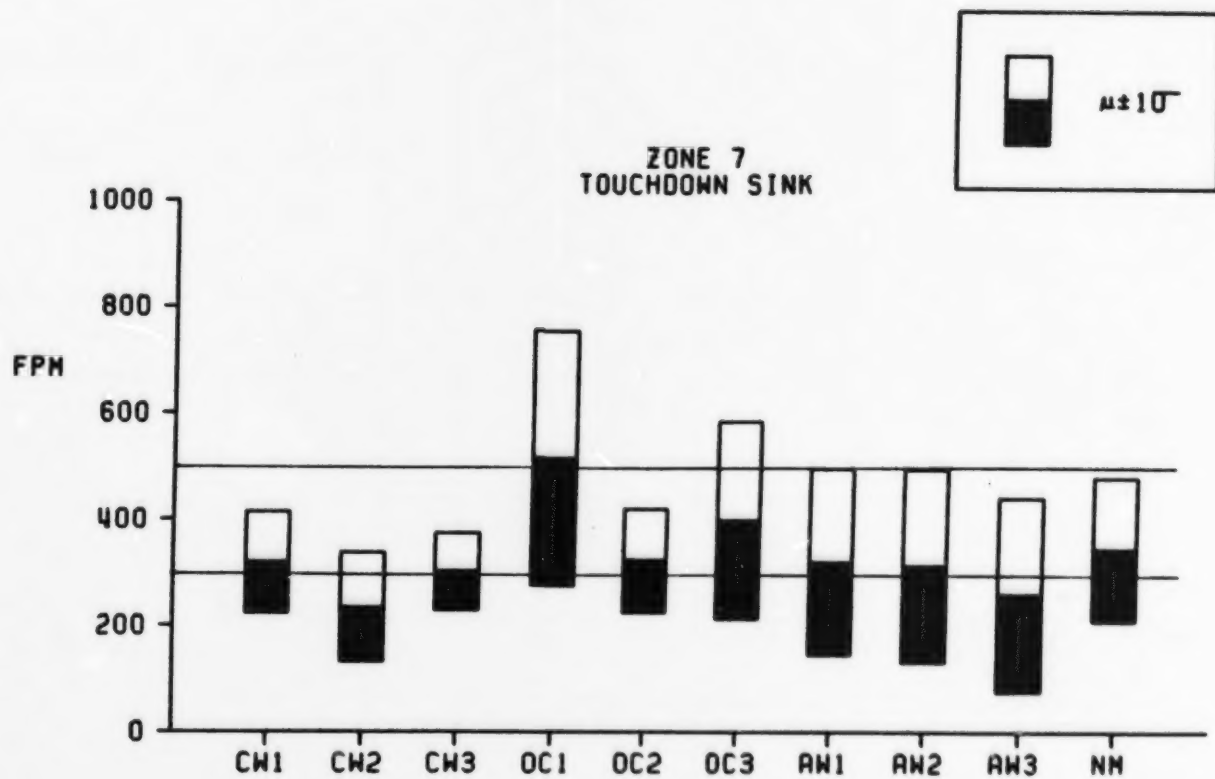


FIGURE 5 TOUCHDOWN RATE OF DESCENT

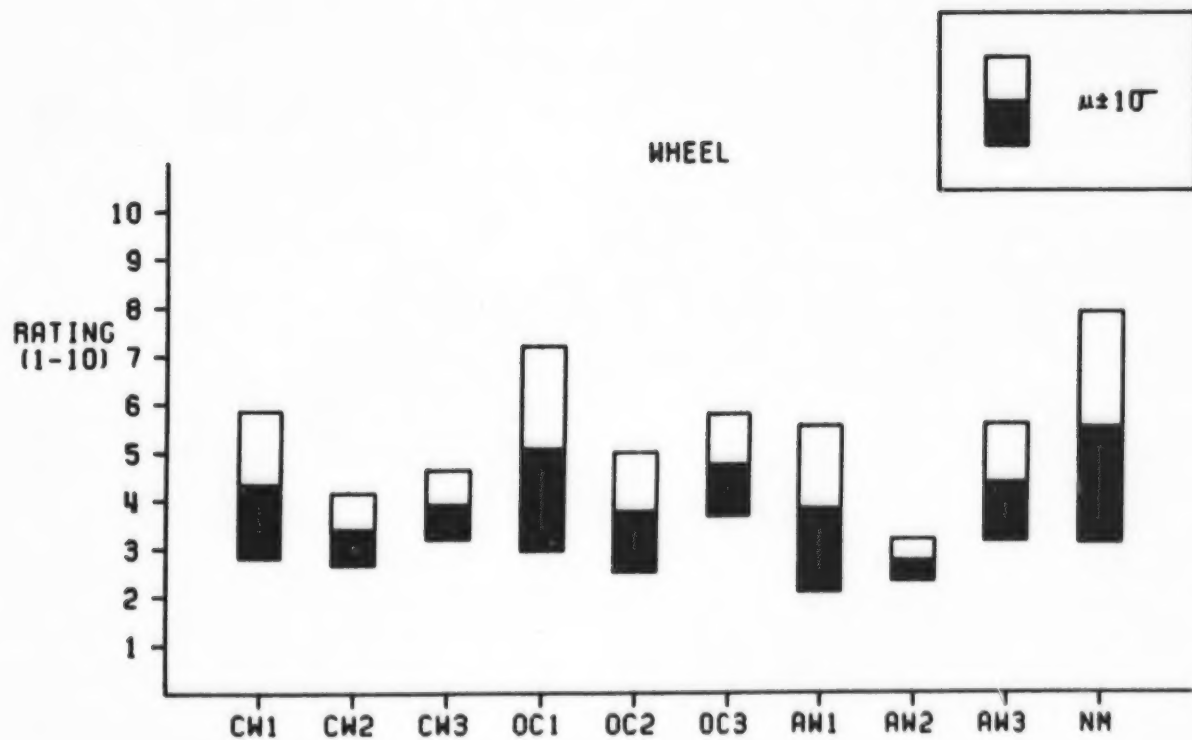


FIGURE 6 PILOT RATINGS OF RESPONSE TO WHEEL INPUTS

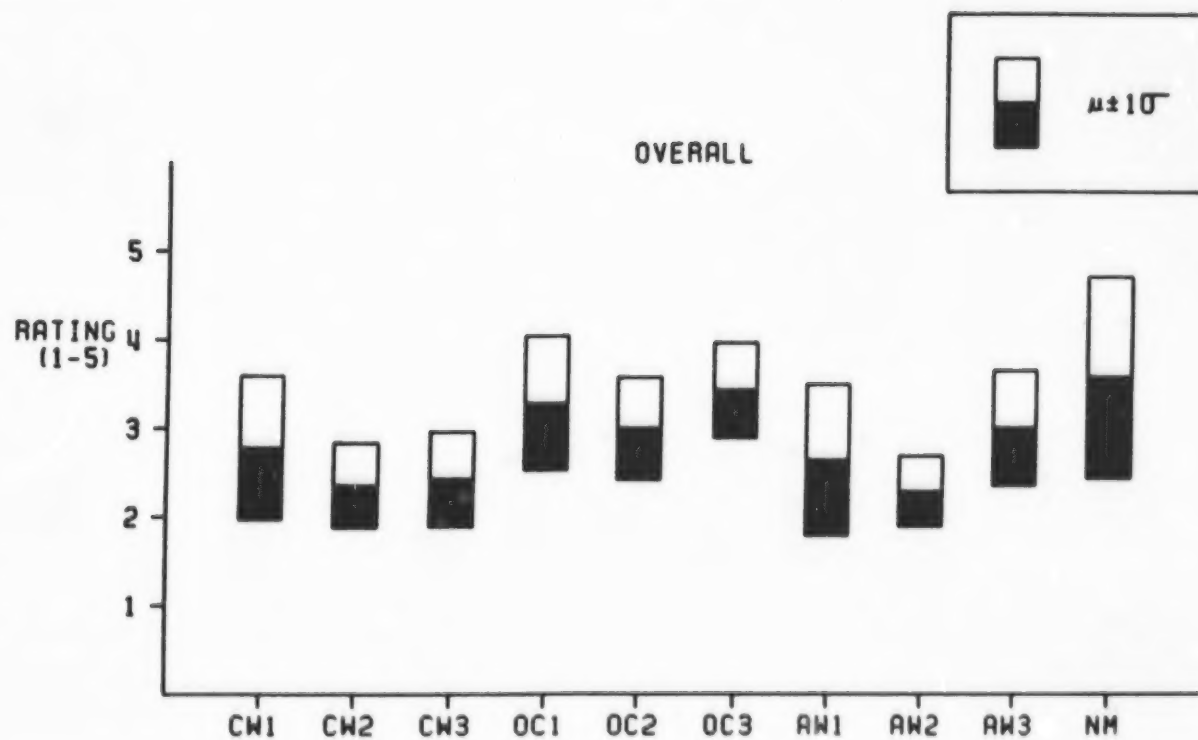


FIGURE 7 OVERALL PILOT RATINGS